

## **APPENDIX E**

---

### **DESCRIPTION OF THE CONCEPTUAL MODEL FOR LOWER COLUMBIA RIVER JUVENILE SALMONIDS**

# 1 INTRODUCTION

Appendix E describes an ecosystem-based conceptual model for juvenile salmonid production in the lower Columbia River. Development of a conceptual model was initially proposed at the first Sustainable Ecosystems Institute (SEI) Science Panel Workshop for the Columbia River Navigation Channel Improvements Project (the Project) (March 17-18, 2001). The model emphasizes juvenile salmonids, which are also the emphasis of the reconsultation process. This approach was proposed in response to the SEI Science Panel's suggestion that it would be helpful to present the ecological relationships for the lower Columbia River in a systematic framework.

The purpose of this conceptual model is to organize the available information on the lower Columbia River ecosystem that pertains to rearing and outmigration of juvenile salmonids. It was thought that organizing the information into a model would help the science panel and members of the interagency consultation and management teams to visualize how various components of the ecosystem connect and function together, and how actions associated with the navigation improvement project may affect the ecosystem as a whole. The model is also a tool to help guide discussions on the most appropriate mitigation (if required), monitoring strategies, and adaptive management.

A substantial amount of information about the lower Columbia River ecosystem and the proposed project has been developed; however, it is contained primarily in lists and extensive text from unrelated sources. The model provides a simple set of diagrams that illustrate the relationships among the various components of the ecosystem; its selected components highlight the more important linkages for the model output, which is successful juvenile salmonid migration to the ocean. In addition to graphically displaying the ecosystem, the model provides a guide for determining what types of data may be most important in understanding long-term component relationships and could be gathered during a monitoring program.

The model, which was developed over a period of approximately 6 months is based on published information and consultation with experts on the lower Columbia River ecosystem. Staff from Battelle Marine Science Laboratories prepared the model with assistance by staff from Parametrix, Inc., and the Port of Portland. Also, individuals from several organizations provided critical review and input, including the Port District of the U.S. Army Corps of Engineers, Port of Portland, National Marine Fisheries Service, U.S. Fish and Wildlife Service, Parametrix, Inc., Limno-Tech, Inc., University of Washington, and Battelle Marine Sciences Laboratory. The SEI Science Panel also provided comments on various versions of the model during the SEI Science Panel Workshops.

## ***Definition of a Conceptual Model***

Huggett (1993) describes a conceptual model as follows:

“...a conceptual model expresses ideas about components and processes deemed to be important in a system, and some preliminary thoughts on how the components and processes are connected. In other words, it is a statement about the system form and system function.”

Huggett also makes the following points regarding conceptual models:

“Conceptual models are expressed in several ways: as pictures, as box-and-arrow diagrams, as matrix models, as computer flow charts, and in various symbolic languages...the old saw is generally true, one picture is worth a thousand words...”

“Conceptual models help to clarify loose thoughts about how a system is composed and how it operates...they are often the foundation for the construction of mathematical models...it is the most important step in the entire process of mathematical modeling.”

Conceptual models have been used widely in ecology to depict ecosystems and food webs (e.g., Odum, 1988; Odum and Hornbeck, 1997; Jackson, et al., 2001; McIntire and Colby, 1978). The conceptual model developed here is what Huggett (1993) terms a box-and-arrow model. In this type of model, boxes stand for system components and arrows depict important links and relations between the components.

### ***Purpose of the Conceptual Model***

In general, a conceptual model is developed to ensure a shared vision of the relationship between components of the ecosystem. A conceptual model functions as a formulation tool, a communications tool, and an assessment tool. Properly constructed, a conceptual model enhances stakeholder participation and minimizes ecological risk. Furthermore, combining the conceptual model with a decision process and framework enables a planning team to deal with risk and uncertainties in a systematic way.

The lower Columbia River conceptual model is used to identify the connection between the actions associated with the Project and the physical and biological reactions to such actions, based on the best available information on qualitative and conceptual relationships. The model provides an integrated picture of the major ecosystem components and those factors that affect ecosystem structure and functioning relative to juvenile salmon. It represents the consensus among the reconsultation stakeholders about how the lower river ecosystem operates. Finally, this conceptual model with its linked submodels representing major ecosystem pathways is a “living” concept that can be refined and revised as new insight and interpretation become available.

### ***Objectives of the Model***

The specific objectives of the lower Columbia River model are to:

- Identify links among physical-chemical and biological components and processes
- Aid in the identification of ecosystem and salmon vulnerabilities and potential effects of the project
- Inform decision-making about the proposed project effects by providing a system-level scientific perspective
- Provide a framework for monitoring and adaptive management

### ***Approach to Model Development***

The model was developed through a synthesis of published and unpublished information, as well as expert input, coupled with the application of ecosystem principles. There is both a general belief that the Columbia River estuary is important, if not critical, to juveniles of some salmon species and a lack of fundamental information proving this. According to Bottom, et al. (2001, page 152), “...the intrinsic assumption that food or predation in the estuary may limit juvenile salmon productivity, or that there are carrying capacity limitations for juvenile salmon in the Columbia River estuary, has never been rigorously tested.” In the opinion of Bottom, et al. (2001) the complex relationships among the many factors affecting salmon, together with the primary producers in the food web, prey production and availability, and salmonid vulnerability to predators, make modeling difficult. This degree of complexity became clear in the development of the model. However, the estuary ecosystem theoretically can be visualized in a conceptual manner that is useful sorting out key ecological interactions.

The primary publications used in developing the conceptual model are listed below. These publications represent both primary reports of new research as well as synthesis documents. The white papers and presentations developed for the reconsultation process were also consulted.

*An Ecological Characterization of the Pacific Northwest Coastal Region: Volume One—Conceptual Model and Volume Three—Characterization Atlas, Zone and Habitat Descriptions* (Proctor, et al., 1980). This set of publications is a comprehensive compilation of information on estuarine and outer coastal systems in the Pacific Northwest. The presentation is organized by conceptual models of the various ecosystems in the region.

*A Review of the Effects of Dams on the Columbia River Estuarine Environment, with Special Reference to Salmonids* (Weitkamp, 1994). This report contains a food web diagram that includes juvenile salmon.

*Changes in Fluxes in Estuaries: Implications from Science to Management* (Dyer and Orth, editors, 1994). This book contains several papers on the Columbia River estuary prepared by the team conducting research on the estuarine turbidity maximum (ETM).

*Columbia River: Estuarine System* (Small, 1990). This special publication in *Progress of Oceanography* contains papers summarizing research conducted as part of the Columbia River Estuary Data Development Program (CREDDP) program in the 1980s.

*Salmon at River's End: The Role of the Estuary in the Decline and Recovery of Columbia River Salmon* (Bottom, et al., 2001), unpublished. A comprehensive compilation and treatment of the factors contributing to changes in the role the estuary plays in juvenile salmon production.

*Scientific Issues Relating to Temperature Criteria for Salmon, Trout, and Char Native to the Pacific Northwest* (Water Temperature Criteria Technical Workgroup, 2001). A summary report to the Policy Workgroup of EPA Region 10 Water Temperature Criteria Guidance Project.

*Chinook Capacity to Adapt to Saltwater* (Weitkamp, 2001a, unpublished). A summary of data on salinity and juvenile salmonids.

*Prey Consumed in Estuaries* (Weitkamp, 2001b, unpublished). A summary of information on prey eaten by juvenile Pacific salmon in estuaries.

*Variability of Pacific Northwest Marine Ecosystems and Relation to Salmon Production* (Bottom, et al., 1998). Comprehensive description of the pelagic life history of salmon and factors in the system that may affect salmon populations.

*Variability of Estuarine and Riverine Ecosystem Productivity for Supporting Pacific Salmon* (Wissmar and Simenstad, 1998). A companion paper to Bottom, et al. (1998) that addresses the river and estuary life history of salmon and factors in the system that may affect salmon populations.

*Changes in Columbia River Estuary Habitat Types over the Past Century* (Duncan W. Thomas, 1983). This report systematically compares present day (i.e., 1970s) benthic habitat areas with information from surveys conducted in 1868-1873.

*Upstream: Salmon and Society in the Pacific Northwest* (National Research Council, 1996). A comprehensive review by a panel from the National Academy of Sciences of salmon stocks and issues related to salmon decline and recovery in the Northwest.

## 2 LOWER COLUMBIA RIVER AND ESTUARY MODELS

Several models have been developed to illustrate how various components of the Lower Columbia system function. Proctor, et al. (1980) provide a series of illustrations that can be used to summarize the fundamental picture of the Columbia River estuarine systems. The relative composition of some of these systems has changed over the past 100 years so that emergent wetlands and above-tide estuarine wetlands have been lost, and deep water habitats, tidal flats and channels have increased in area (Thomas, 1983).

The successional development of these habitats depends on several processes. Through physical processes of deposition, erosion, stabilization, and siltation, vegetation changes occur and the land surface elevation increases, gradually forming forested wetlands and upland habitats (Proctor, et al., 1980). Human-induced alterations of this successional process in the Columbia River estuary include diking, grazing, dredging, and changes in flow (Sherwood, et al., 1990). Elevation and hydrology are key factors that control the types of habitats and functions each habitat performs. Therefore, altering primary and secondary rate controlling factors – either by restricting hydrology (through diking or changing elevation by filling or dredging) or by changing erosional and deposition processes through alterations in river flow or sediment supply – will result in a modification of habitat distribution and function.

Sherwood, et al. (1990) summarized the changes that have occurred in the estuary. Their study reported that the tidal prism had been reduced approximately 15 percent and there had been a net increase in sediment in the estuary. Sediment had eroded from the entrance and been deposited on the continental shelf. Reduced river flow resulted in less mixing, increased stratification, altered response to tidal forcing, and decreased salinity intrusion length and transport of salt into the estuary. There had been an estimated 82 percent reduction in emergent wetland production and a 15 percent reduction in benthic microalgae production. Riverine detritus derived from freshwater phytoplankton production had increased to partially compensate for this loss. This increase caused a shift in the food web from macrodetritus from emergent marshes to more labile microdetritus from allocthonous phytoplankton. The shift favored suspension-feeding copepods associated with the ETM, such as *Eurytemora affinis* and the harpacticoid copepod *Scottolana canadensis*. Sherwood, et al. (1990) postulated that production of these species over benthic deposit-feeding invertebrates resulted in a fundamental shift from support of a benthic-feeding to a pelagic-feeding fish fauna. Estuarine-dependent juvenile salmon feed primarily on benthic prey, and this fundamental shift in the food web may have affected the quality and quantity of prey available to these fish.

The decrease in flows caused by flow regulation has resulted in less variation in the location of both the toe of the salt wedge and the ETM. Extensive research on the ETM by Simenstad, et al. (1994) and others indicates that the position of the ETM and the excursion of salty water are driven by tides and river flow. The ETM and salinity may play an important role in the food web as well as in structuring the benthic community (including important salmonid prey such as *Corophium*).

Weitkamp (1994) describes a food web for the estuary that highlights the sources of prey to salmonids in the estuary, including *Daphnia*, insects, mysids and *Corophium*. The latter three taxa are supported by marsh carbon, whereas *Daphnia* is supported by the resident phytoplankton and freshwater microdetritus pathway. The microdetritus pathway supports a set of piscivorous birds and mammals known to prey on juvenile salmon in the estuary. The degree to which this shift in the food web has affected salmonid production and survival is not quantified.

Salmonids exhibit several life-history strategies, which are believed to maximize the ability of the species to withstand variation in the system. For ocean-type chinook salmon, there may be as many as 35 potential life-history strategies (Wissmar and Simenstad, 1998). Of relevance to the estuary is that chinook are known to spend time ranging from brief periods (days) to extended periods (6 months) rearing and feeding in the estuary. The net effect is that there may be populations of juvenile chinook in the estuary throughout much of the year. Because of seasonal changes in habitats and prey resources, caused by changes in forcing factors, the salmon use a seasonally varying array of habitat conditions and prey resources. Consequently, the support provided by the estuary for survival, growth, smolting, and passage varies.

According to Wissmar and Simenstad (1998), juveniles that are highly estuarine dependent are known to feed on a variety of prey, including insects and amphipods. However, the author caution that the food web pathway can be highly variable because of differential pulses of organic matter and the heterogeneous distributions of living and detrital food sources across estuarine habitats. This variability may explain dramatically different trophic support of salmon, especially when salmon localize their rearing and migrations in a specific estuarine region or habitat. Furthermore, production at lower trophic levels may not be a realistic indicator of estuarine production support for salmon because of this variability.

Bottom, et al. (2001) proposed two criteria for evaluating the “opportunity for subyearling, ocean-type, salmon to use habitat for their benefit.” Their review of information on use of estuarine habitats in the Pacific Northwest indicated that depth and velocity were potentially useful in defining the areas most frequently utilized. These salmonids generally were found in the depth zone of 0.1 to 2.0 meters (m) in the water column and in areas where current velocities were on the order of 30 centimeters per second (cm/s) or less. These life-history types were generally oriented toward shallow channels and marsh edges where benthic prey are abundant. Based on these criteria, Bottom, et al. (2001) showed that habitat opportunity was altered by bathymetry and flow changes in the system when compared to pre-dam conditions. In combining their findings related to large-scale alterations in flow characteristics with the knowledge that marshes have been lost and changes in carbon sources have occurred, they concluded that the productive capacity of the estuary has likely declined over the last century.

The relationship between changes in the Columbia River and its estuary are complex. Bottom, et al. (2001) present a comprehensive assessment of large-scale historical changes in the estuary relative to salmon. However, evaluation of smaller-scale changes, such as those relevant to the channel improvements project, is being approached from a variety of directions by various agencies. Some key issues that need to be included in this latter assessment are:

- Availability of specific (especially shallowwater) habitats used during rearing and outmigration through the estuary
- Effects of physiochemical and biological conditions on estuarine residence times, growth, and survival
- Food chain relationships among juvenile salmon, invertebrate prey, and vertebrate predators
- Differences in these estuarine habitat needs and ecological relationships among salmon species, life-history types, and source populations

## 2.1 General Model Overview

The general form of a conceptual model is typically formatted to flow from the general to the specific, as shown below:



This form assumes that ecosystem functions are determined by ecosystem structure and that ecosystem structure is controlled by physical and chemical processes. The model form can be applied to the Columbia River Navigation Channel Improvement Project reconsultation process by defining the historical, present (i.e., project baseline), and potential state of the ecosystem relative to the project. Figure E-1 illustrates a conceptual matrix for the ecosystem state. It is assumed that there is a positive relationship between structure of an ecosystem and function of that ecosystem, and that the natural climax or optimal structure of an ecosystem has a corresponding and predictable functional condition.

	Rudimentary Structure	Intermediate Structure	Climax or Optimal Structure
Optimal Functioning			Desirable Ecosystem Condition
Intermediate Functioning		Acceptable Ecosystem Function	
Low Functioning	Unacceptable Ecosystem Function		

**Figure E-1 Conceptual Ecosystem State**

As shown, system structure and function are divided into three levels: low, moderate, and high conditions. The values (e.g., acreage) used to quantify the structural condition (e.g., the size of the pond-wetland interface) and the functional conditions (e.g., the number of ducks nesting at this interface) can occupy a range (e.g., from 80 to 100 square meters of pond-wetland area). Using a range of values acknowledges two primary sources of uncertainty:

- Present understanding of the relationship between structural and functional ecosystem components
- Natural variability associated with structural conditions and functional conditions target (Shreffler and Thom, 1993; Hobbs and Norton, 1996; Thom, 2000)

As noted by Bottom, et al. (2001, 1998); and Wissmar and Simenstad (1998), the Columbia River salmon populations have been subjected to variations in climate and other factors and have, to a certain degree, adapted their life-history strategies to deal with these variations. Prior to human influence, the Columbia system underwent extensive variability in the ecosystem conditions that form the structural aspects of habitats used by salmon. Flow regulation has reduced variability in river discharge, which is potentially a major influence on habitats and their use by salmon (Bottom, et al., 2001). Flow regulation and tidal wetland and swamp loss have been identified as two of the most important changes in the lower Columbia River relative to salmonids. Because of these two major changes, the lower Columbia River ecosystem is

likely in an altered state. Whether that state is acceptable depends on the interpretation of the situation. As with other system states, natural variation in ecosystem conditions within this altered state is expected and will not shift the system condition to a lower or higher state.

The conceptual model for the lower Columbia River ecosystem, which is described in the remaining sections, illustrates the relationships among the structural and functional conditions of the system. In addition, the model is a summary of what is understood about controlling factors responsible for the formation of the structural and functional aspects of the ecosystem. The conceptual model, coupled with the general matrix shown in Figure E-1, provides a framework by which the effects of changes in structure, function, and controlling factors on salmon can be assessed.

## **2.2 Conceptual Model Description**

This section begins with a brief discussion of migratory patterns for juvenile and adult salmon, but focuses on juvenile salmon outmigration. The integrated model and component pathways are emphasized.

### ***Major Migratory Behaviors***

Juvenile salmon use the lower Columbia River system for a variety of purposes; adults primarily use the system to move upstream to spawning grounds but may also feed in it. At some point in their first or second year, juvenile salmon begin their outmigration from their natal stream down through the estuary to the open ocean. Success in reaching the ocean depends on their ability to:

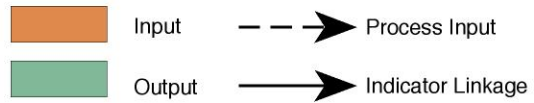
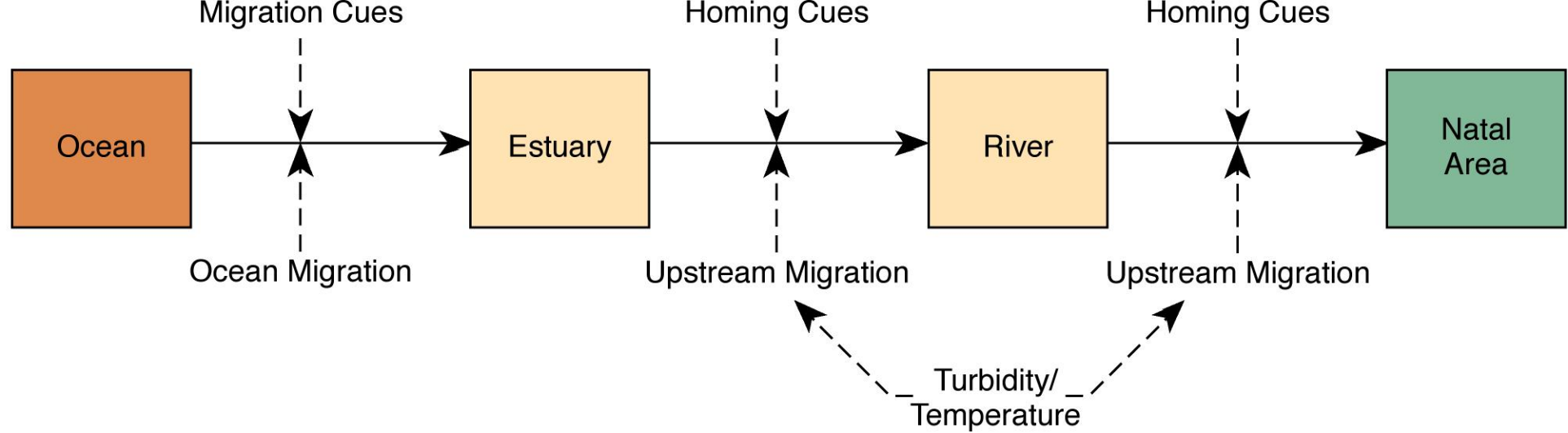
- Easily move between the various zones within the migratory corridor
- Transition physiologically between fresh and salt water environments
- Feed and grow substantially
- Avoid predation

(Wissmar and Simenstad, 1998; Brodeur, et al., 2000; Bottom, et al., 2001),

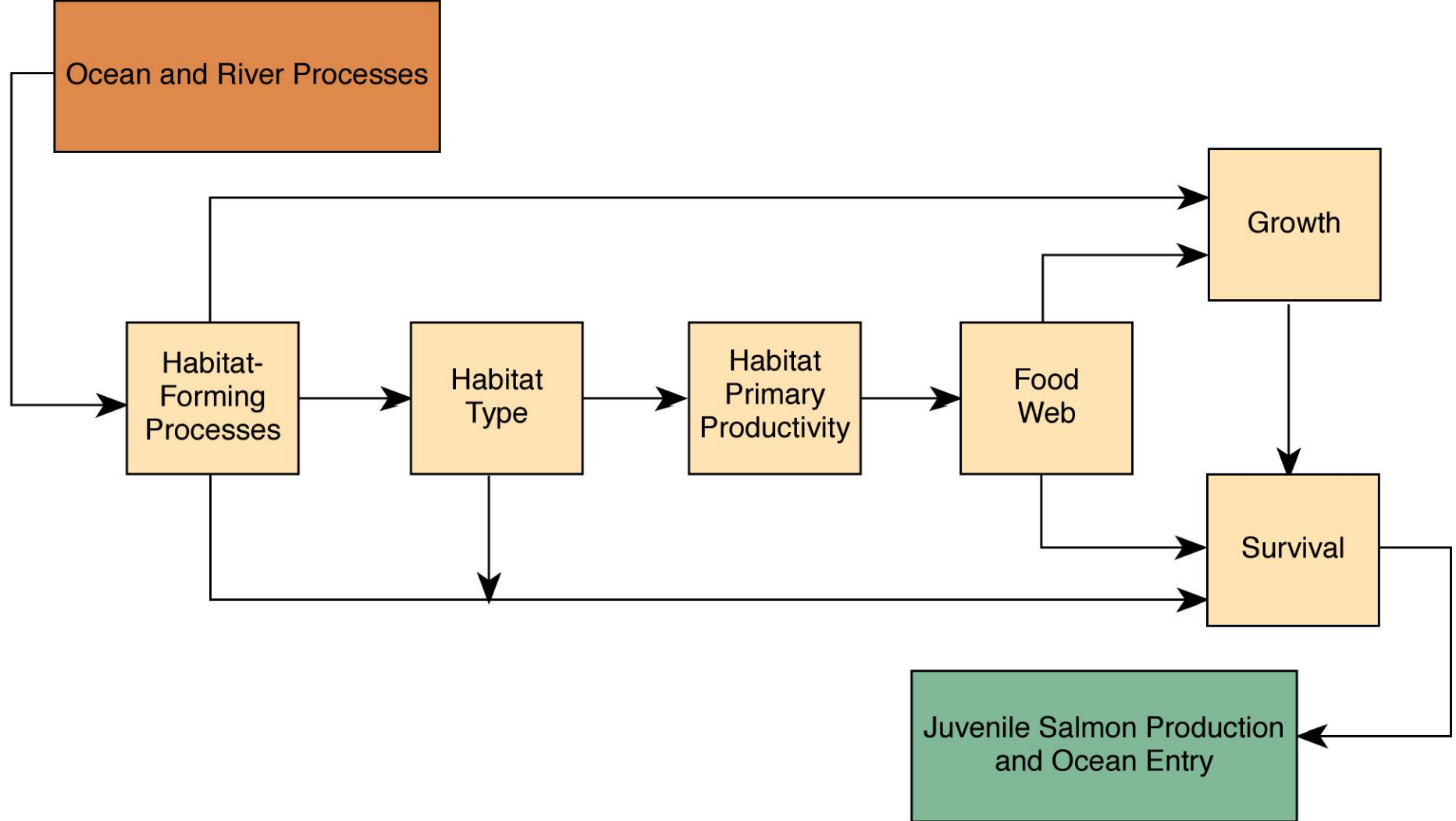
During return migration, adult salmon rely on various homing cues to relocate the mouth of the river as well as their natal spawning grounds (Figure E-2). Migration to their spawning grounds depends on an open connection between the ocean and the natal area as well as the ability of the fish to find its way. According to a report by the National Resource Council (NRC, 1996) both extreme temperatures and increased turbidity may affect the ability of fish to find their way or may restrict the upstream rate of movement. Higher temperatures, combined with lower levels of dissolved oxygen in the water, may stop migration until conditions improve. Bottom, et al. (1998) and the NRC (1996) concluded that salmon survival is affected by ocean conditions and that variability in ocean conditions strongly influences salmon abundance.

### ***Integrated Conceptual Model for Juvenile Salmon***

The Integrated Conceptual Model illustrates the major components of the estuarine ecosystem relative to juvenile salmon (Figure E-3). The output from the model is juvenile salmon production and ocean entry. According to a similar model in Brodeur, et al. (2000), salmon production and ocean entry depend on several functions, including the development of habitats, production of food to fuel the food web, and ability to access and use these habitats. The culmination of these functions results in growth and survival of fish and their ultimate entry into the ocean.



**Figure E-2**  
**Adult Salmonid Migration**  
**Returning to their Natal Stream**



**Figure E-3**  
**Integrated Model for Juvenile Salmonids**  
**in the Lower Columbia River**

Taken as whole, the model highlights the complexity of the factors supporting juvenile salmonid production and ocean entry. Benefits provided to salmonids in the lower Columbia can be summarized as the ability of salmonids to access habitats (i.e., habitat opportunity) and the amount of food available within these habitats (i.e., habitat capacity), as discussed in Bottom, et al., 2001. In turn, opportunity and capacity depend on the development and functioning of viable habitats. These habitats are formed and maintained by physical and chemical forcing factors. Significant interactions affect the development of habitat as well as its support to salmonids. These interactions include habitat succession rates and patterns, disturbance regimes, landscape connectivity, and salmonid life-history diversity.

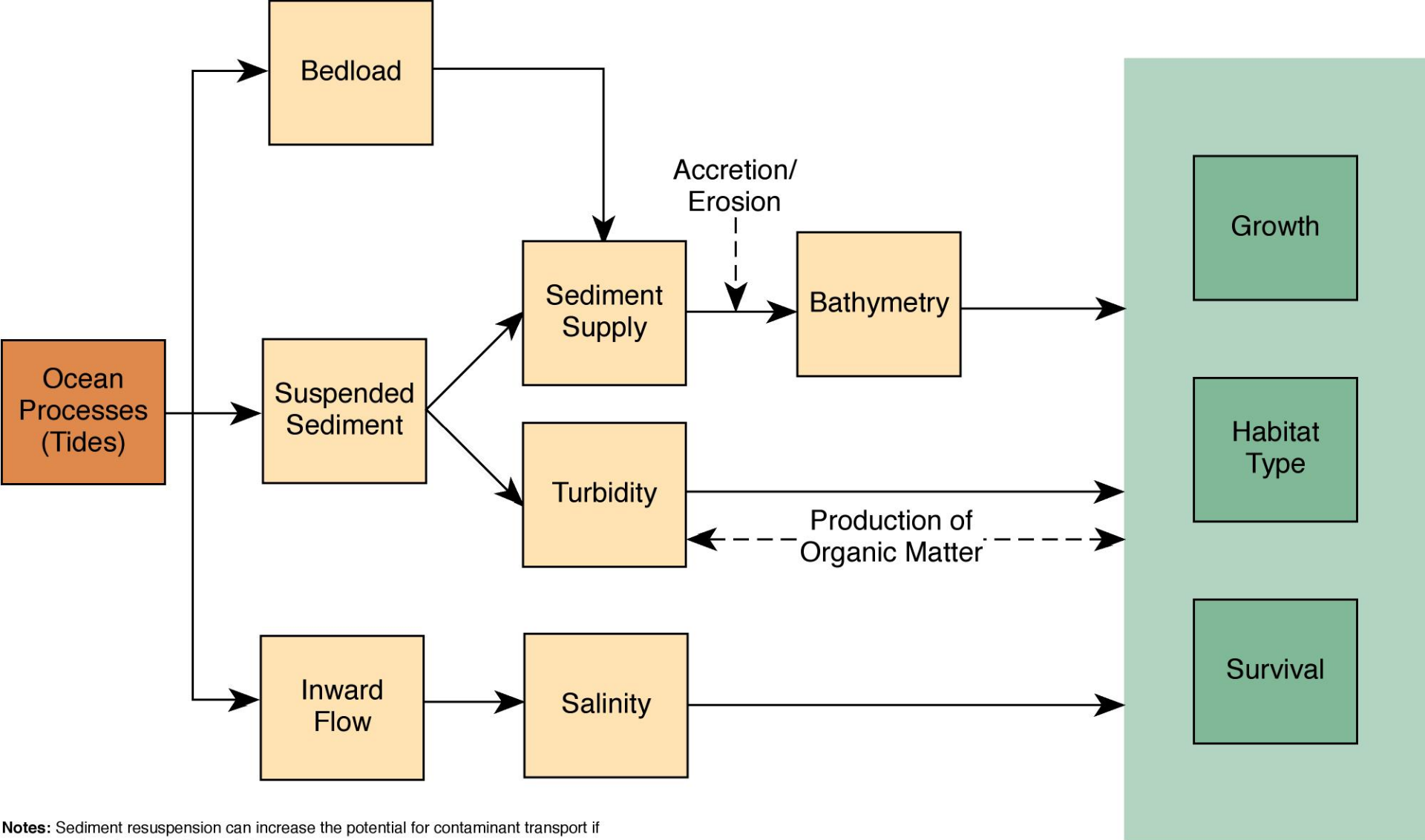
Salmon can be grouped into river type and ocean type. The river type is more dependent on the lower Columbia for migration and water column feeding opportunities, whereas the ocean type spends more time in the estuary and feeds in shallow water habitats. Each type is believed to have several variations in life-history strategies. For ocean-type chinook, this number may be as high as 35 (Wissmar and Simenstad, 1998). The variation among life-history strategies occurs in the timing and relative length of time spent in the estuary. Theoretically, evolution of a diverse set of strategies guards against complete elimination of a species because of large natural variations in the system. Both ocean and river types undergo physiological changes to acclimate to salt water while in the estuary. Each type can be subject to predation as well as contaminants and other stressors. Bottom, et al. (2001) believe that an important point for transition occurs in the oligohaline zone.

### ***Habitat-Forming Processes***

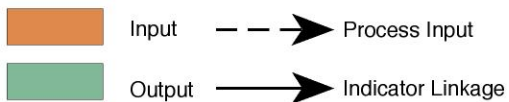
The Habitat-Forming Processes Pathways illustrate the factors and interactions involved in the formation and maintenance of lower Columbia River habitats (Figures E-4a and E-4b). The main factors affecting or “explaining” habitat development include salinity and bathymetry (i.e., elevation). Woody debris is a special case of a distinct habitat that enters into the estuary from upstream sources. Turbidity and contaminants also affect habitat quality. Contaminants may affect the quality and quantity of food available for salmonids as well as salmonid health.

Habitats are formed primarily by hydrological processes: flow rates, volumes, and dynamics. In the lower Columbia, the river and the ocean influence the hydrodynamics. River flow rates and volumes are regulated by precipitation, temperature (e.g., freeze and thaw), and dam operations. Ocean processes, including tidal action and waves, interact in the lower Columbia with river hydrodynamics. The net result is deposition (accretion) of sediment to form flats and carving (erosion) to form shallow and deep channels. Where sediments form stable islands, marsh and swamp vegetation can develop. These marshes and swamps are dissected by shallow channels, which provide access for fish to the edges of the vegetated areas. Broad intertidal sand flats and mud flats form where sediments are somewhat unstable and where the elevation is not high enough for marshes to develop.

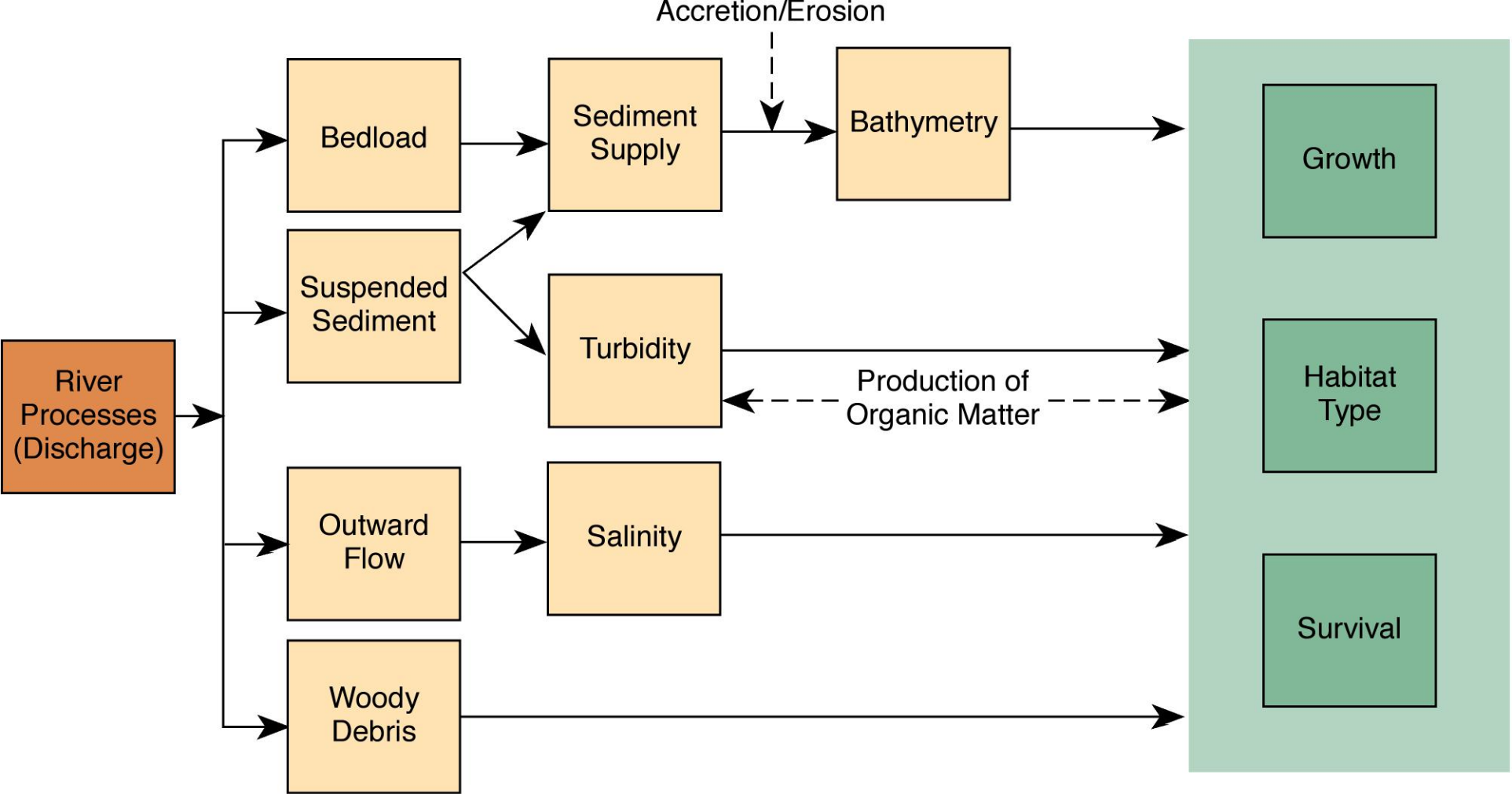
Large woody debris is also deposited on the flats, in channel edges, and in marshes and swamps. Woody debris creates a vertical structure to which fish often orient, as well as small “micro” habitats that can trap organic matter and be rich in invertebrate animals. The relative role of woody debris as a habitat for salmonids in the Columbia River estuary or any other estuary in the Pacific Northwest is not well studied (Simenstad, pers. comm., 2001). Anecdotal observations show that salmonids will congregate near large woody debris, and feeding may be enhanced because of the deposition of organic matter and the production of small benthic prey animals.



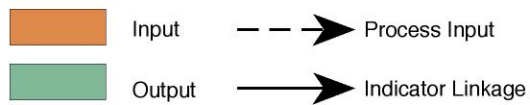
**Notes:** Sediment resuspension can increase the potential for contaminant transport if sediments are contaminated.  
 Habitat-forming processes are affected by natural disturbance regimes including:  
 1) extreme hydrological events, 2) vertical land movement, and 3) storms.



**Figure E-4a**  
**Habitat-Forming Process**  
**Pathway – Ocean**



**Notes:** Sediment resuspension can increase the potential for contaminant transport if sediments are contaminated.  
 Habitat-forming processes are affected by natural disturbance regimes including:  
 1) extreme hydrological events, 2) vertical land movement, and 3) storms.



**Figure E-4b**  
**Habitat-Forming Process**  
**Pathway – River**

Because plants and animals prefer certain ranges of salinity, the level, seasonal, and spatial patterns of salinity strongly influence where species occur in the lower Columbia. Mixing of fresh and salt water in the Columbia estuary results in a gradient in salinity in the estuary. The zone of mixing varies dramatically (i.e., tens of miles) in location, depending on river flow and tides. The salt wedge forms a zone of intense mixing, breaks up phytoplankton produced upstream, and results in increased microbial activity and turbidity (Simenstad, et al., 1994).

Salinity ranges that occur in estuaries are grouped into the categories shown in Table E-1. The oligohaline zone (the zone where juvenile salmonids go through a physiological transition to a saltwater environment) is of particular relevance to salmon. Animals may spend a considerable period of time in the oligohaline zone, where they require adequate food supplies and refuge from predators to survive and grow.

**Table E-1 Salinity Zones**

<b>Zones</b>	<b>Salinity Range (ppt)</b>
Hyperhaline	> 40
Euhaline	30.0 – 40
Mixohaline (brackish):	0.5 – 30
Polyhaline	18.0 – 30
Mesohaline	5.0 – 18
Oligohaline	0.5 – 5
Fresh	< 0.5

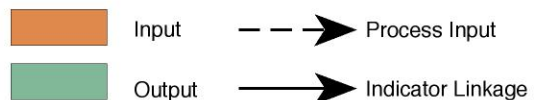
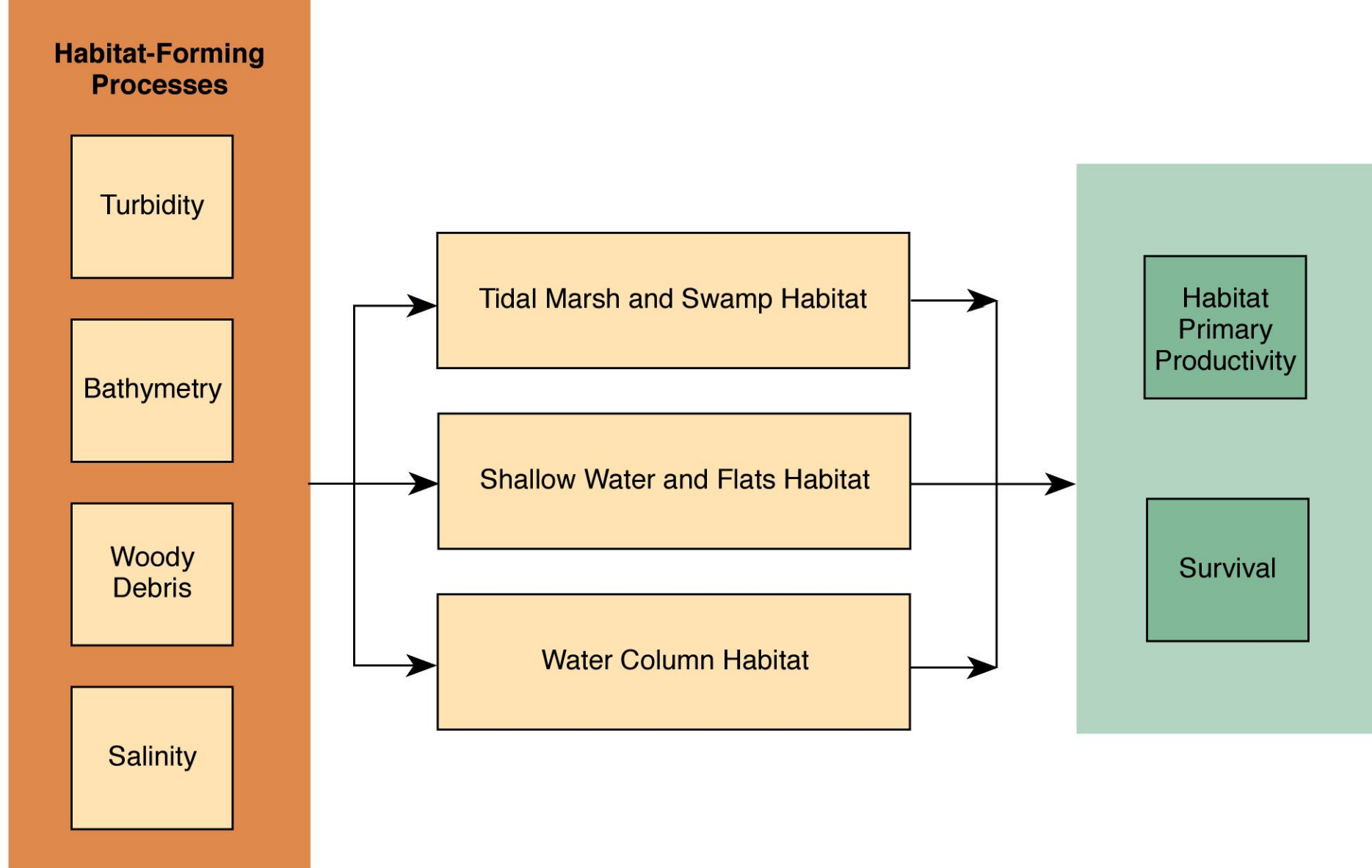
Source: Modified from Cowardin, et al., 1979.

The zone of intense biological activity and physical interactions where this mixing occurs is the ETM. As in many estuaries, turbidity from suspended sediment and plankton is moderate to high in the lower Columbia. High river flows and heavy wind and wave activity can increase turbidity dramatically. Because plants need light to grow, turbidity affects how deep plants can grow below the water surface. Higher turbidity means that plants can grow only very near the surface of the water. Rooted aquatic plants such as eelgrass (*Zostera marina*) are generally limited to very shallow depths in the estuary because of turbid water.

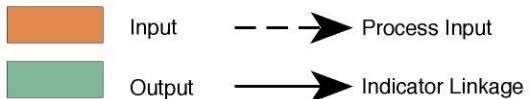
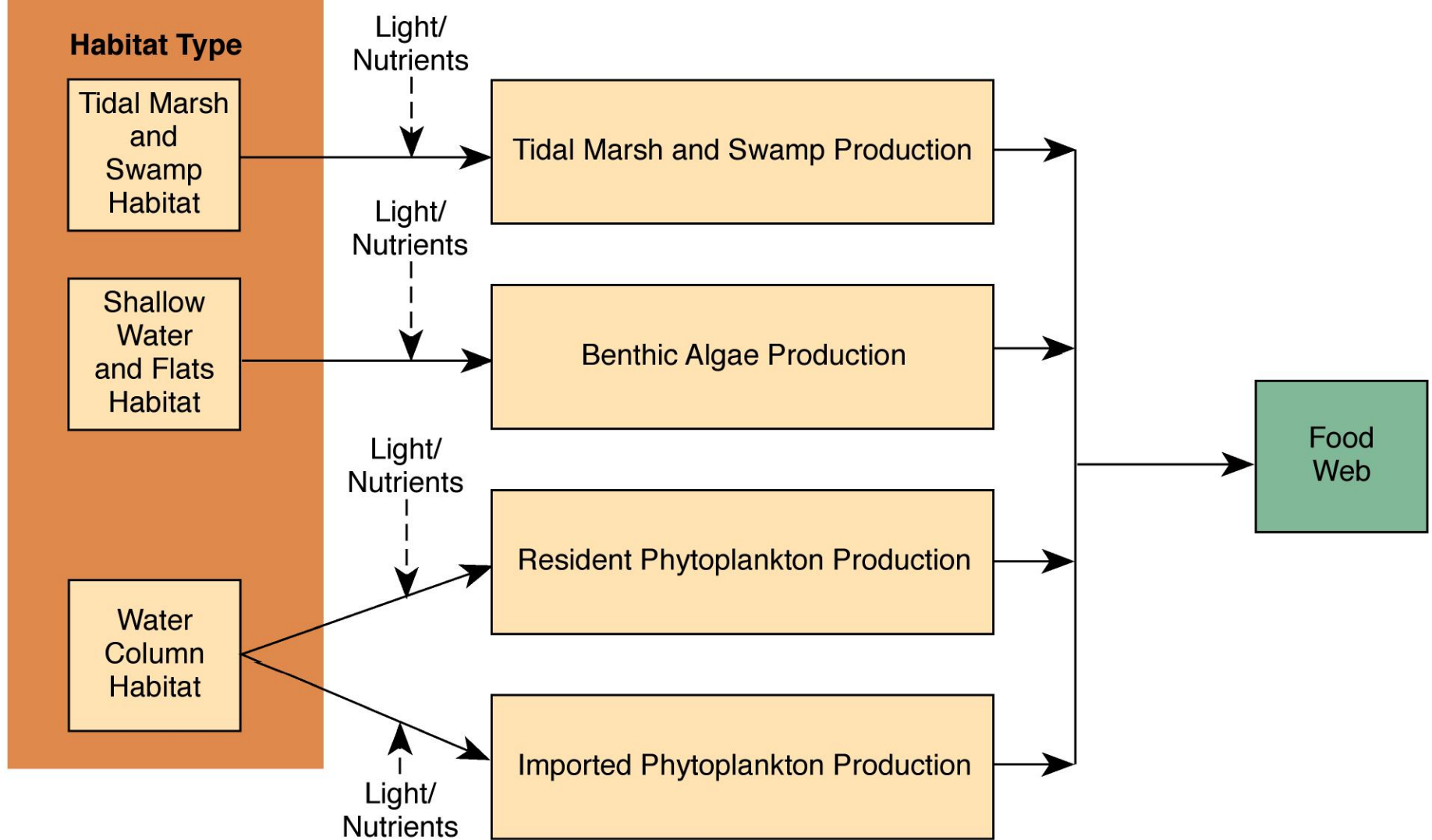
As shown in the Habitat Forming Processes Pathways (Figures E-4A and E-4b), all of these dynamics and interactions culminate in the creation of habitat types important to salmon in the lower Columbia. The functions of the types of habitats created are further developed in the Habitat Type Pathway (Figure E-5), and the Habitat Primary Productivity Pathway (Figure E-6).

### ***Habitat Types***

The habitats most directly linked to salmonids in the lower Columbia River include the water column, the flats, and the tidal marshes (including swamps). Physical processes active in the river and ocean form these habitats. Because the project area is physically dynamic, the locations and functions of the habitats are adapted for this situation and also exhibit dynamic features.



**Figure E-5**  
**Habitat Type Pathway**



**Figure E-6**  
**Habitat Primary Productivity Pathway**

Habitat types are generally restricted to specific elevation ranges (Figure E-7 ). Marshes and swamps occur from about mean high water to above. Flats occur throughout the intertidal zone and into the shallow subtidal zone. Water column vegetation can be stratified by depth. For example, the upper 1 to 3 meters of the water column can have a very different community than deeper zones. This stratification is caused by both the salinity variation and the light penetration by depth. The elevation gradient is driven by tolerances of the plants to withstand immersion as well as drying (desiccation) and light. For example, the depth to which eelgrass can grow is limited by light penetration (Thom, et al., 1998). The upper limit is controlled by plant intolerance to drying during low tides.

At a given elevation, there is an overriding influence of salinity in development of these habitat types. Tidal marshes can be divided into saltwater marshes and freshwater marshes, each characterized by a distinctive vegetation type. There are extensive tidal freshwater marshes in the lower Columbia, in particularly those in Cathlamet Bay. Benthic algae, largely benthic diatoms, develop on tidal flats and in the shallow subtidal zone in the system. The water column habitat is essentially the location of phytoplankton and floatable organic matter. Both phytoplankton and zooplankton respond to changes in salinity. Freshwater plankton dominates the fresh and oligohaline portion of the system, and plankton tolerant of greater salinity dominates the estuary and the mouth of the system.

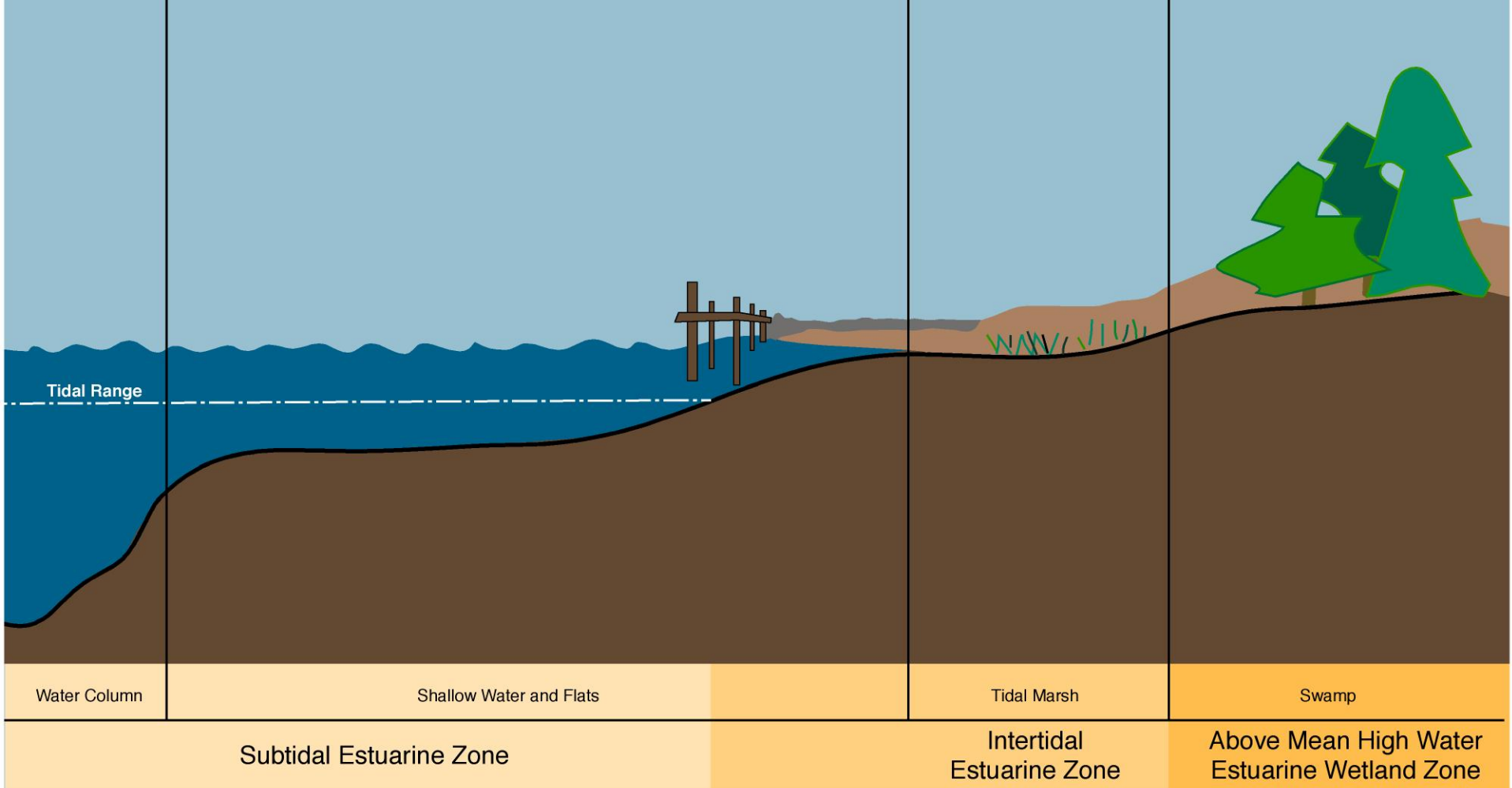
There is a growing understanding that juvenile salmon use the edges of tidal marshes to feed and the edges of channels as low-tide refuge and feeding areas (Simenstad and Cordell, 2000). Consequently, access to the edges at high tide and development of low-tide refuge areas near or within marshes are important. Channel order (the number and width of channels) and channel depth are a function of marsh area. Although there are no empirical data on this relationship for the Columbia River, smaller marshes would provide limited salmonid access and only limited nearby low-tide refuge areas. Large marshes provide access to a much greater amount of edge and provide low-tide refuge.

A major function of the habitats is to produce food used by the ecosystem. Food production is driven by the growth of plants, which is termed *primary productivity*. Habitat-specific primary productivity is described in the following subsection.

### ***Habitat Primary Productivity***

The food consumed by young salmon in the lower Columbia derives its energy from a variety of sources. The detrital food web supported by plant material from marshes, benthic algae, and the water column is particularly important. All of the habitats are described in the Habitat Type Pathway. Plants in these three habitats make up the bulk of the primary production, or plant growth, in the system. They not only produce organic matter within plant tissue but also export dissolved organic matter to the ecosystem (McIntire, 1984).

Primary productivity is driven by light, and the growth of the plants is supported by inorganic nutrients (e.g., nitrate, phosphate). Inorganic nutrients enter the system from the river and the ocean and also from cycling of organic matter in the system. Factors that affect the distribution of the plants within the system include the habitat-forming processes of sedimentation, erosion, salinity, and turbidity (Section 5, Figures 5-2a and 5-2b). As turbidity increases, light in the water column is reduced. This reduction in light can result in less phytoplankton growth as well as limit the depth of submerged plants.



**Figure E-7**  
**Major Habitat Types in the System**

The plants in the system can be divided into resident and imported. Resident refers to the phytoplankton, benthic algae, and marsh vegetation produced within the lower Columbia River. Imported material, primarily phytoplankton and floating organic matter, enters the system at Bonneville Dam; it is largely produced in the reservoirs upstream of Bonneville Dam. The material produced in the lower Columbia and imported to the system includes material in various stages of disintegration and decay. It has become customary to describe larger particles of organic matter as macrodetritus and very small particles as microdetritus. Small animals that shred the larger plant matter and microbes, such as bacteria, protozoa, and fungi, facilitate the breakdown of the detritus. Besides making the organic matter useful to the food web, the breakdown process results in the recycling of inorganic nutrients needed by the plants.

As illustrated in the Food Web Pathway in the next section (Figure E-8), the live plant material and detritus are the primary sources of organic matter in the food web used by salmonids in the lower Columbia River.

## 2.3 Food Web

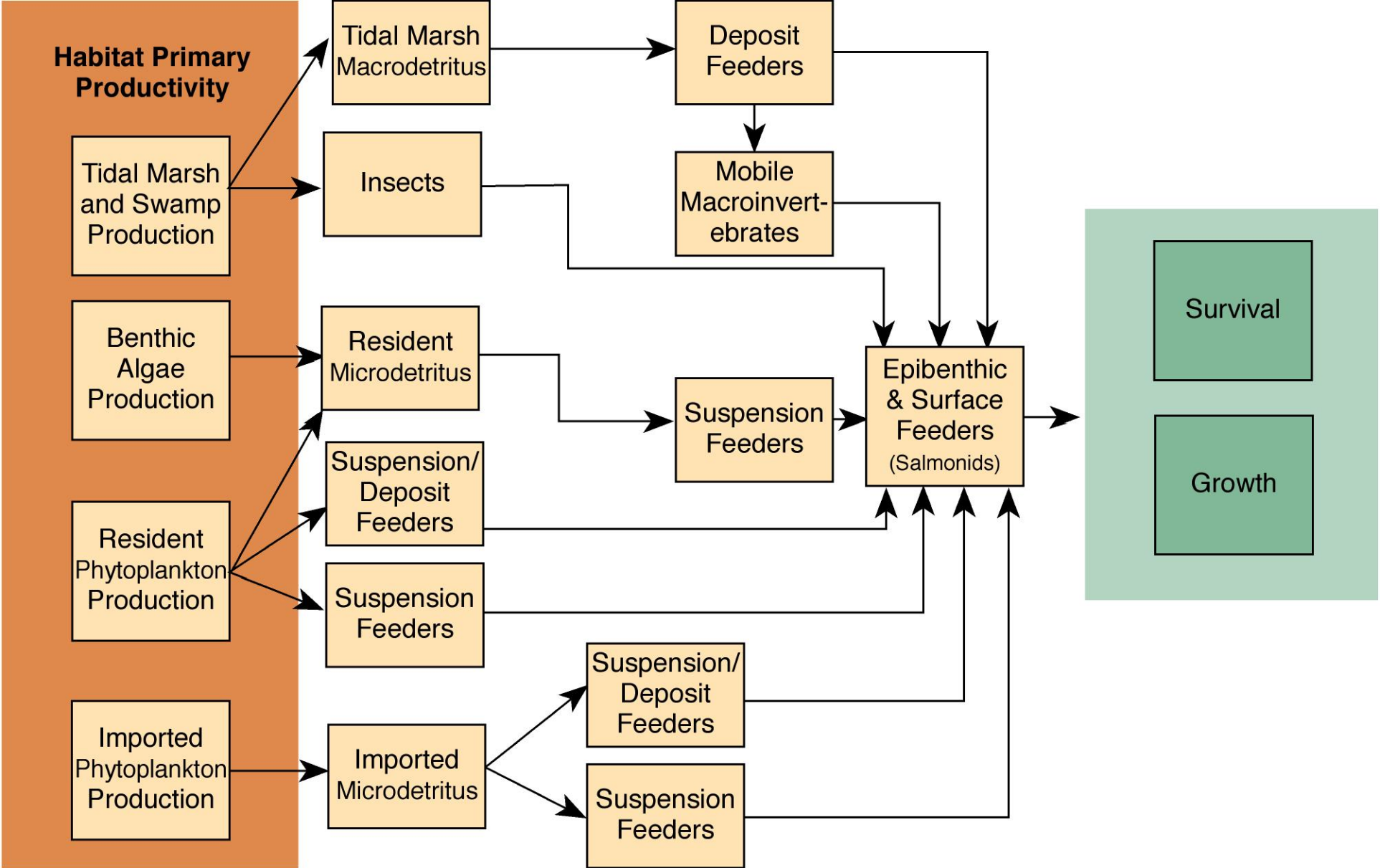
Along with the functions of refuge, rearing, and reproduction, feeding is a key function of estuaries to salmonids. A food web is an illustration of who eats what in an ecosystem. The importance of constructing a food web is to develop a complete understanding of the ways in which a member of the food web obtains its food. The food web can be used to provide insight about what food items might be absent, potentially limiting the growth of members of the food web.

As illustrated in the Food Web Pathway (Figure E-9), juvenile salmonids are members of a complex food web in the lower Columbia. The model represents only the salmonid portion of the total food web for the system, which is far more complex (Weitkamp, 1994). The energy sources at the base of this web as shown at the left side of Figure E-9, are derived from the Habitat Primary Productivity Pathway (Figure E-6). Live plants can be eaten directly or decaying material (detritus) can be incorporated into the food web through the detritivores (animals that eat dead and decaying plants and animals) (Jones, et al., 1990).

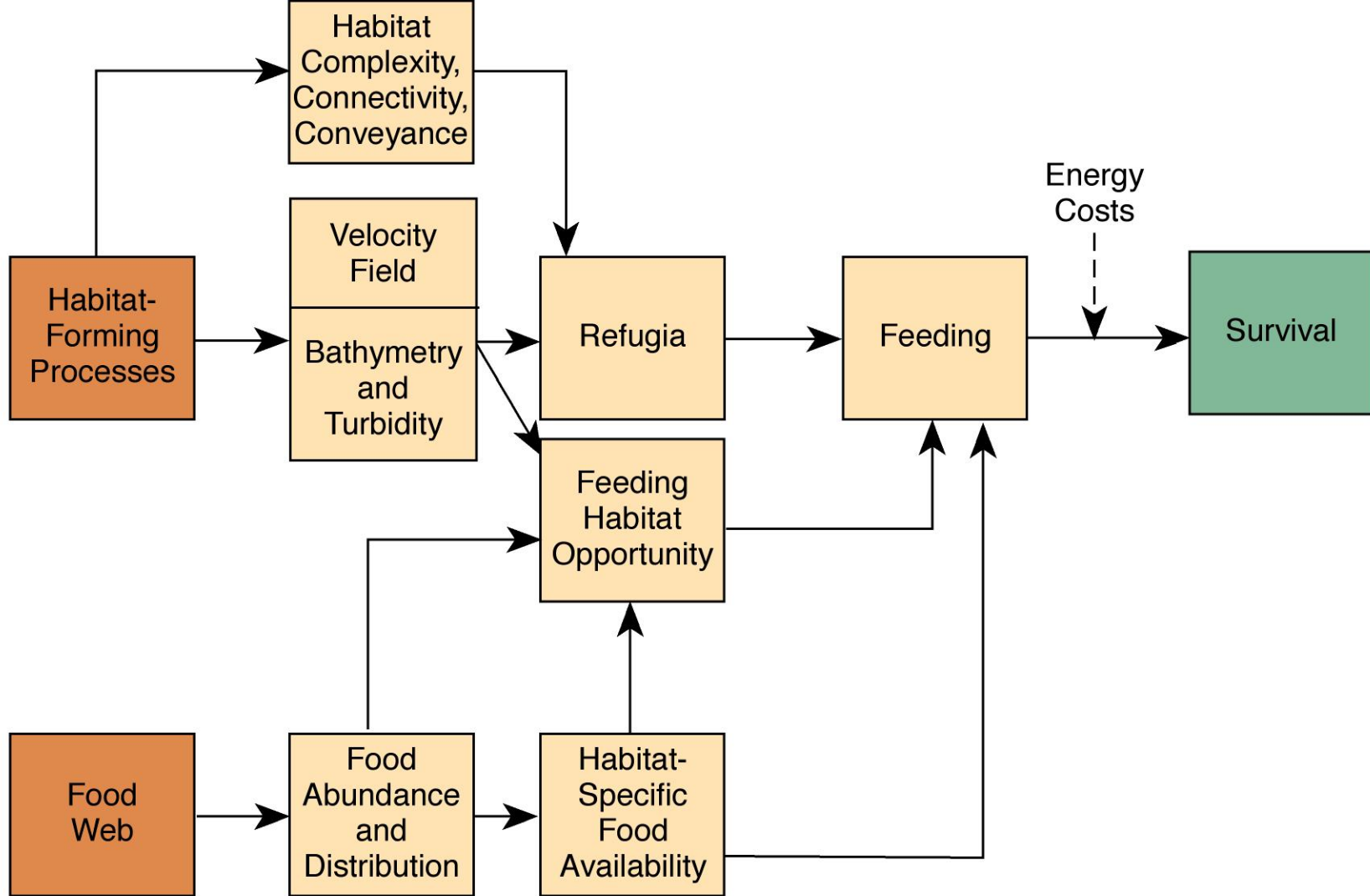
Although the Food Web Pathway does not show the relative amounts of food derived from each primary producer type, it does illustrate that salmonids can and do use prey species supported by resident and imported plankton and detritus as well as resident marsh plant material. The relative amount of food depends on the abundance of each resident habitat type (e.g., tidal marshes) and the input of nonresident material from upstream sources. The latter input is controlled primarily by production in the reservoirs behind the dams as well as flow rates from Bonneville Dam.

Invertebrates that salmonids consume occur in the water column and on the river bottom. Among the most abundant species found in the stomachs of salmonids are a benthic amphipod (*Corophium salmonis*) and a planktonic cladocera (crustacean), *Daphnia*. Subyearling chinook feed primarily on the bottom while they are in the lower Columbia, whereas older (yearling) fish of all species feed primarily on zooplankton in the water column.

Floating insects (larvae and adults) appear to be important in the diet of most of the species and age classes. Many of these insects feed on live tidal marsh plants.



**Figure E-8**  
**Food Web Pathway**



**Figure E-9**  
**Growth Pathway**

The location of these prey species' production is important. Because outmigrating juvenile salmon are often found in the upper 2 meters of the water column, they probably are not using benthic (bottom-dwelling) prey in deeper parts of the estuary. For this reason, the primary range of feeding depths for salmon feeding on benthic prey is the intertidal zone down to a depth of about 2 meters below Extreme Lower Low Water. Insects, *Corophium*, and mysids located in shallow habitats such as tidal marshes, tidal channels, and flats are more available to salmonids at higher tides. Planktonic prey such as *Daphnia* and copepods are available at any stage of the tide.

Salmonid feeding results in growth of the animals in preparation for their outmigration to the North Pacific. The Growth Pathway (Section 5, Figure 5-10) incorporates feeding as well as other factors that are involved in producing salmonid growth in the lower Columbia.

## 2.4 Growth

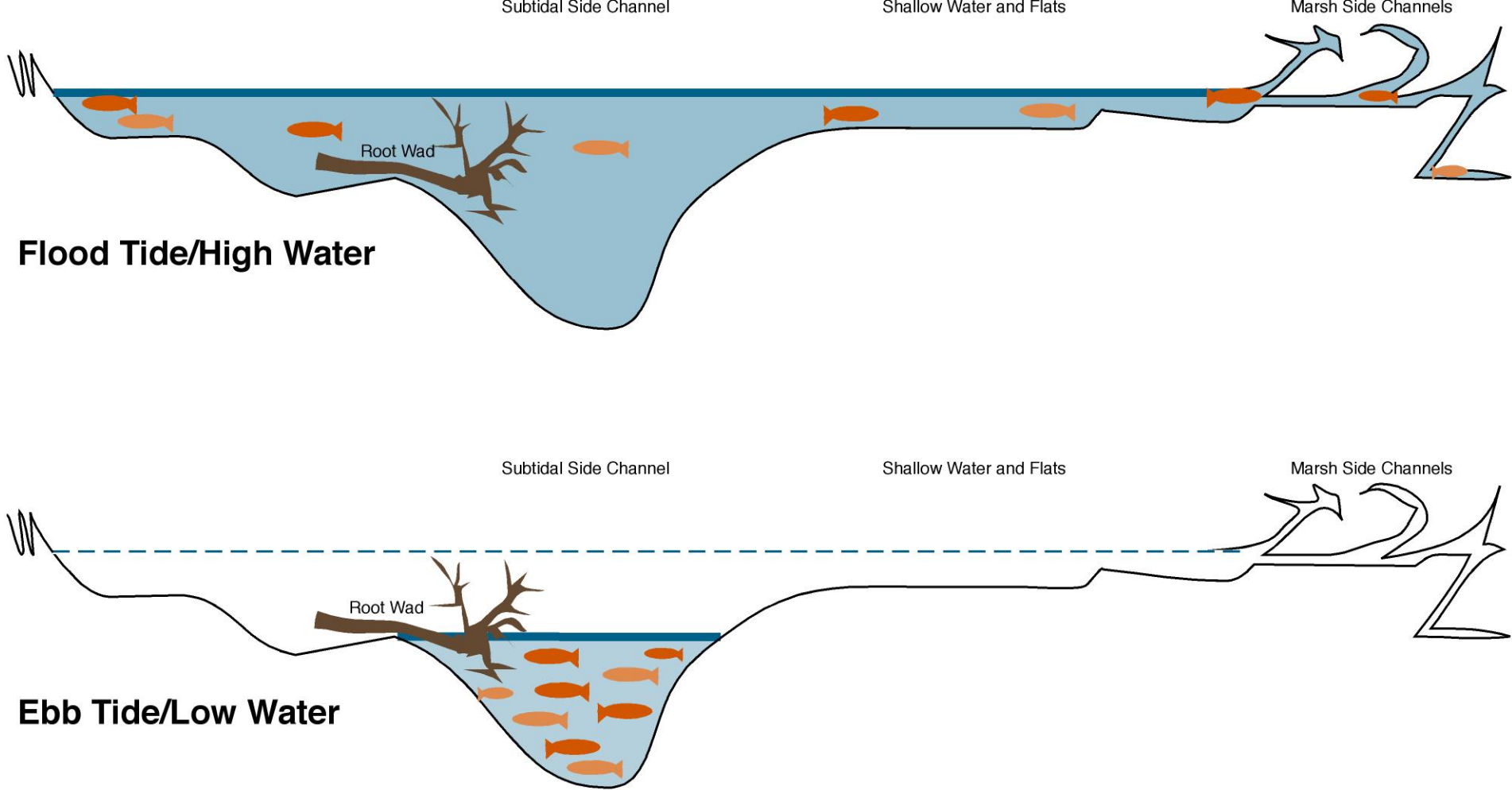
The pathways leading up to the Growth Pathway (Figure E-9) show the progression from physical factors involved in creating habitats in the lower Columbia River through the ways in which these habitats work to produce food for salmonids. The Growth Pathway highlights the factors involved in producing the amount of, and access by fish to, productive feeding areas.

The characteristics of the food web, such as the abundance of insects versus the biomass of nonresident microdetritus, and where this material is distributed are important in the relative contribution of the material to growth of salmonids. The "Food Abundance & Distribution" and "Habitat-Specific Food Availability" boxes in the Growth Pathway (See Figure E-9) illustrate this line of logic. The actual locations and structure of feeding habitats are important because the fish must first be able to access feeding habitat and then be able to find the prey items.

Salmonids are adapted for using a complex mosaic of habitats during their residence in estuarine systems in the Northwest. Therefore, they require the opportunity to feed within the set of habitats, combined with habitat-specific food production. Simenstad and Cordell (2000) identified the following elements as relevant to habitat use opportunities for juvenile salmon:

- Tidal elevation, which is directly related to frequency and duration of tidal flooding
- Extent of geomorphic features, such as total edge and penetration of tidal channels
- Proximity to disturbance
- Actual or perceived refuge from predation
- Strength of cues that might attract salmon

Most fish live primarily in very shallow water, especially the subyearling chinook. They benefit most from prey produced in tidal marshes, in marsh channels, on the edges of deeper channels, and on flats. Fish move up over flats and into tidal marsh systems as the water level rises and falls with the tide and with river flow (Figure E-10). When water level is low, fish are thought to congregate at the edges of deeper channels and pools (low-tide refuges). Longer channels provide deeper penetration of fish into a marsh, and thereby access to more marsh-edge habitat. This mosaic of available habitats is called habitat complexity. An absence or reduction in the natural complexity of habitats available to the fish may have an impact on their ability to reach food resources needed for growth.



**Figure E-10**  
**General Pattern of Lower Columbia River**  
**Use by Juvenile Salmonids**

Connectivity refers to the connections between habitats in the mosaic. In the lower Columbia, this refers to the connection between viable feeding and refuge habitats along the migratory corridor. Blockages or interruptions of corridors may limit access to productive feeding habitats. For example, a culvert may block fish access to tidal marsh behind a river levee. Large numbers of over water structures may restrict the ability and migration habits of fish traveling along the shoreline. Because fish are adapted for use of a wide but linked set of habitats, maintenance of free access among habitat types is an important component of feeding habitat opportunity. This concept is illustrated in the Growth Pathway (See Figure E-9).

Still, shallow areas provide productive feeding areas for salmonids. Because juveniles are small and have relatively weak swimming capabilities, feeding is most effective in areas where current velocities are slow. Although not well understood or studied, velocities of 30 cm/s or less are considered best for optimal foraging opportunity (Bottom, et al., 2000). Because salmonids are visual predators, turbid waters may limit their ability to see prey. Again, little is understood about this phenomenon in the context of Northwest estuarine systems. Velocity field, shallow bathymetry, and turbidity are illustrated in boxes at the left of the Growth Pathway (See Figure E-9).

Finally, each individual animal expends energy to feed. These energy costs include those associated with locating prey, feeding behavior, avoiding predators, and processing energy from the prey consumed. In general, fish prefer high-energy food, which provides the most energy per unit of effort. Anything less will, theoretically, produce suboptimal growth rates.

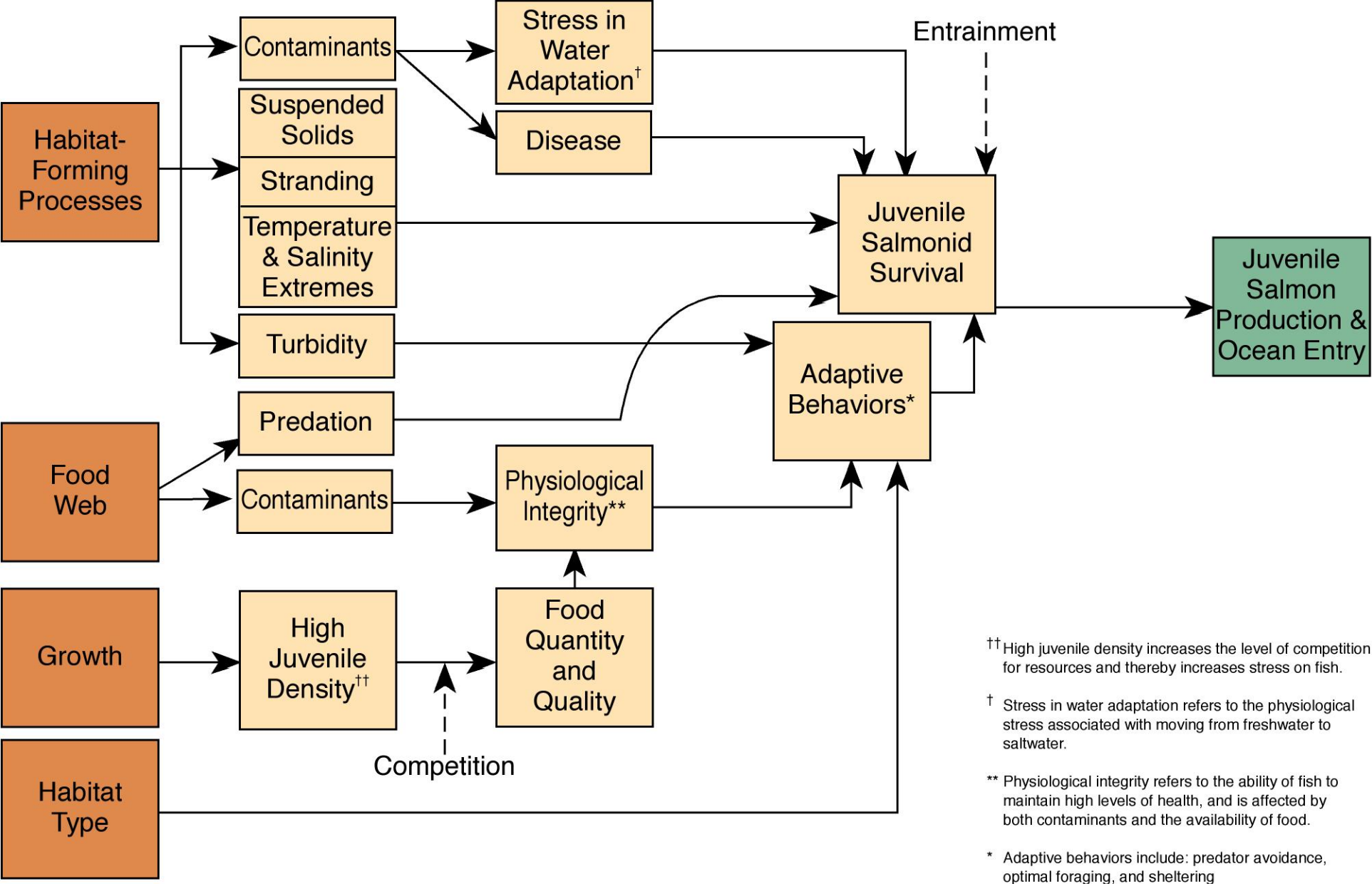
Besides growth, a variety of interacting factors affect the ultimate survival of salmonids in the lower Columbia River. The Survival Pathway (Figure E-11) describes what is understood about these factors.

## **2.5 Survival**

Salmonid survival depends on an ability to grow and migrate through the lower Columbia River system (see Figure E-11). As shown in the previous pathways, a complex set of factors controls or affects growth and migration. The Survival Pathway is a summary of these key factors.

Factors that can negatively affect survival include contaminants, predation, suspended solids, temperature and salinity extremes, stranding, and competition. In addition, fish may be entrained during dredging operations.

Contaminants include those chemicals that affect the health of fish. They can be taken up directly through the water column and indirectly through contaminated prey throughout the food web. The prey of juvenile salmon may obtain contaminants via their food sources. For example, contaminants deposited on the bottom along with organic matter may be ingested by deposit-feeding animals, which are in turn ingested by salmon. Contaminants can affect the health (physiological integrity) of fish, with a net effect of impaired health from disease as well as a reduced ability to physiologically adapt to salt water, avoid predators, forage effectively, and seek and find shelter.



**Figure E-11**  
**Survival Pathway**

Predation is a major factor affecting fish survival in the lower Columbia River. Birds, such as western grebes, cormorants, gulls, terns, and great blue herons, are known to prey on small fish, which may include young salmon. Surprisingly, few fish that prey on juvenile salmon have been verified by actual examination of the gut contents of the suspected predators. In a review of existing information, Simenstad, et al. (1999) found a relatively long list of potential predators, but only two species (Pacific staghorn sculpin and Cutthroat trout) were verified as preying on juvenile salmon.

Suspended solids, which can be a major contributor to turbidity, affect migratory ability by reducing the fish's ability to see prey. Data indicate that the threshold concentration for survival of ocean type salmonids is on the order of 1 gram per liter (Weitkamp, 2001).

Both abnormally high temperatures and high salinity will stress fish. These conditions can occur during extreme low flow conditions in summer, with shallow flats and channels being the zones of most intense heating.

Stranding can occur when fish are washed up onto higher ground by waves or boat wakes, or if they are caught for extended periods of time in a shallow pool during an extended low tide. Observations by fisheries biologists in the system indicate that some stranding does occur.

Competition among members of the outmigrating population may play a role in survival; however, little is understood or documented regarding the effects of competition in a system such as the lower Columbia.

Entrainment refers to the uptake of fish by the dredge during dredging. Because dredging takes place primarily at the deepest portions of the channel, bottom-dwelling fish are more susceptible to entrainment. Surface-oriented fish such as salmonids may be less susceptible.

Adaptive behavior improves the probability that fish will survive. The adaptive behaviors of predator avoidance, optimal feeding (foraging) in the system, and ability to find refuge are all enhanced if fish are healthy. As described earlier, fish health depends on the physiological integrity of the fish as well as the availability and quality of habitats.

### **3 SUMMARY DISCUSSION**

The conceptual model represents the current understanding of the lower Columbia River ecosystem relative to juvenile salmon. It has aided in the identification of links among the physical and biological structures and processes in the estuary. The model indicates that flow, depth, salinity, temperature, and sediment appear to be driving the structure and function of the estuary ecosystem in terms of supporting the essential needs of juvenile salmon for survival, growth, saltwater adaptation, and passage.

The actual organization of the model changed several times during its development as a result of both corrections and refinement. The need to make the model understandable to as many people as possible, without sacrificing technical accuracy, was also important; consequently, much of the process involved simplifying the model. For example, the food web developed by Weitkamp (1994) was simplified considerably to include only the major taxa directly linked to juvenile salmon. An additional effort was made to link the Pathways to one another to ensure that anticipated changes in physical conditions could be followed through the entire model to their links with biological components.

The model highlights those connections most relevant to assessing the effects of navigation channel improvements on juvenile salmon. Once these effects have been identified, more in-depth analysis can be undertaken, which may include the development of a numerical model. For example, because possible

changes in salinity were of concern, numerical modeling was used to evaluate the effects that a deeper channel could have on salinity intrusion (Weitkamp, 2001; Reed, et al, 1994). The modeling results were then used as input to the conceptual model in order to assess the impacts that changing the locations of feeding and physiological transition would have on salmonids.

## 4 REFERENCES

- Bottom, D.L., J.A. Lichatowich, and C.A. Frissel. 1998. "Variability of Pacific Northwest Marine Ecosystems and Relation to Salmon Production" (Chapter 5). In *Change in Pacific Northwest Coastal Ecosystems*. Gregory R. McMurray and Robert J. Bailey, editors. Proceedings of the Pacific Northwest Coastal Ecosystems Regional Study Workshop, August 13-14, 1996, Troutdale, Oregon. NOAA Coastal Ocean Program Decision Analysis Series No. 11. Silver Spring, Maryland: NOAA Coastal Ocean Office. Pp.181-252
- Bottom, D.L., C.A. Simenstad, A.M. Baptista, D.A. Jay, J. Burke, K.K. Jones, E. Casillas and M.H. Schiewe. 2001 (unpublished). *Salmon at River's End: The Role of the Estuary in the Decline and Recovery of the Columbia River Salmon*. Draft Report. Seattle: National Marine Fisheries Service.
- Brodeur, R.D., G.W. Boehlert, E. Casillas, M.B. Eldridge, J.H. Helle, W.T. Petersen, W.R. Heard, S.T. Lindley, and M.H. Schiewe. 2000. "A Coordinated Research Plan for Estuarine and Ocean Research on Pacific Salmon." *Fisheries* 25:7-16.
- Dyer, K.R., and R.J. Orth, editors. 1994. *Changes in Fluxes in Estuaries: Implications from Science to Management*. Fredensborg, Denmark: Olsen & Olsen.
- Hobbs, R.J., and D.A. Norton. 1996. "Towards a Conceptual Framework for Restoration Ecology." *Restoration Ecology* 4:93-110.
- Huggett, R.J. 1993. *Modelling the Human Impact on Nature*. Oxford University Press.
- Jackson, J.B.C., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Petersen, R.S. Steneck, M.J. Tegner, and R.R. Warner. 2001. "Historical Overfishing and the Recent Collapse of Coastal Ecosystems." *Science* 293:629-638.
- Jones, K.K., C.A. Simenstad, D.L. Higley, and D.L. Bottom. 1990. "Community Structure, Distribution, and Standing Stock of Benthos, Epibenthos, and Plankton in the Columbia River Estuary." In *Columbia River: Estuarine System*. Vol. 25. L.F. Small, editor. Progress in Oceanography. Pp. 211-241.
- McIntire, C.D. 1984. Final Report on Benthic Primary Production Work Unit of the Columbia River Estuary Data Development Program. Unpublished.
- McIntire, C.D. and J.A. Colby. 1978. "A Hierarchical Model of Lotic Ecosystems." *Ecological Monographs* 48:167-190.
- National Research Council (NRC). 1996. *Upstream: Salmon and Society in the Pacific Northwest*. National Academy Press.
- Odum, H.T. 1988. Self-Organization, Transformity, and Information. *Science* 242:1132-1139.

- Odum, H.T. and D.A. Hornbeck. 1997. "EMERGY Evaluation of Florida Salt Marsh and its Contribution to Economic Wealth" (Chapter 8). In *Ecology and Management of Tidal Marshes: A Model from the Gulf of Mexico*. Charles L. Coultas and Yuch-Ping Hsieh, editors. St. Lucie Press. Pp. 209-230.
- Proctor, C.M., J.C. Garcia, D.V. Galvin, G.B. Lewis and L.C. Loehr. 1980. Conceptual Model. An Ecological Characterization of the Pacific Northwest Coastal Region. Vol. 1: U.S. Fish and Wildlife Service, U.S. Department of Interior. Vol. 3: Characterization Atlas, Zone and Habitat Descriptions.
- Reed, D.J., and J. Donovan. 1994. The Character and Composition of the Columbia River Estuarine Turbidity Maximum. In *Changes in Fluxes in Estuaries: Implications from Science to Management*. K.R. Dyer, and R.J. Orth, editors. Proceedings of the ECSA22/ERF Symposium, University of Plymouth, England. Olsen and Olsen: Fredensborg, Denmark. Pp. 445-450.
- Sherwood, C.R., D.A. Jay, R.B. Harvey, P. Hamilton, and C.A. Simenstad. 1990. "Historical Changes in the Columbia River Estuary." In *Columbia River: Estuarine System*. Vol. 25. L.F. Small, editor. Progress in Oceanography. Pp. 299-352.
- Shreffler, D.K., and R.M. Thom. 1993. Restoration of Urban Estuaries: New Approaches for Site Location and Design. Prepared for Washington State Department of Natural Resources. Olympia, Washington: Battelle Marine Sciences Laboratory.
- Simenstad, C.A., D.J. Reed, D.A. Jay, J.A. Baross, F.G. Prahl, and L.F. Small. 1994. "Land-Margin Ecosystem Research in the Columbia River Estuary: An Interdisciplinary Approach to Investigating Couplings between Hydrological, Geochemical and Ecological Processes within Estuarine Turbidity Maxima." In *Changes in Fluxes in Estuaries: Implications from Science to Management*. K.R. Dyer and R.J. Orth, editors. Fredensborg, Denmark: Olsen & Olsen. P. 437.
- Simenstad, C.A., B.J. Nightingale, R.M. Thom, and D.K. Shreffler. 1999. Impacts of Ferry Terminals on Juvenile Salmon Migrating Along Puget Sound Shorelines, Phase I: Synthesis of State of Knowledge. Prepared for Washington State Transportation Commission. Seattle: Washington State Transportation Research Center, University of Washington.
- Simenstad, C.A., and J.R. Cordell. 2000. "Ecological Assessment Criteria for Restoring Anadromous Salmonid Habitat in Pacific Northwest Estuaries." *Ecological Engineering* 15:283-302.
- Small, L.F., Editor. 1990. "Columbia River: Estuarine System." Progress in Oceanography. Vol. 25.
- Thom, R.M. 2000. "Adaptive Management of Coastal Ecosystem Restoration Projects." *Ecological Engineering* 15:365-372.
- Thom, R.M., and A.B. Borde. 1998. "Human Intervention in Pacific Northwest Coastal Ecosystems" (Chapter 2), In *Change in Pacific Northwest Coastal Ecosystems*. G.R. McMurray and R.J. Bailey, editors. NOAA Coastal Ocean Program, Decision Analysis Series No. 11. Pp. 5-37.
- Thom, R.M., L.D. Antrim, A.B. Borde, W.W. Gardiner, D.K. Shreffler, and P.G. Farley. 1998. "Puget Sound's Eelgrass Meadows: Factors Contributing to Depth Distribution and Spatial Patchiness." Puget Sound Research '98 Proceedings. Olympia, Washington: Puget Sound Water Quality Action Team. Pp. 363-370.

- Thomas, D.W. 1983. Changes in Columbia River Estuary Habitat Types over the Past Century. Astoria, Oregon: Columbia River Estuary Study Task Force.
- Water Temperature Criteria Technical Workgroup. 2001. Scientific Issues Relating to Temperature Criteria for Salmon, Trout, and Char Native to the Pacific Northwest. Unpublished Summary Report submitted to Policy Workgroup of EPA Region 10 Water Temperature Criteria Guidance Group.
- Weitkamp, D. 2001a. Chinook Capacity to Adapt to Saltwater. Unpublished Draft Report. Bellevue, Washington: Parametrix, Inc. 4 p.
- Witkamp, D. 2001b (unpublished). Prey Consumed in Estuaries. Bellevue, Washington: Parametrix, Inc.
- Weitkamp, L.A. 1994. A Review of the Effects of Dams on the Columbia River Estuarine Environment, with Special Reference to Salmonids. Report funded by Bonneville Power Administration, Portland, and National Marine Fisheries Service, Seattle.
- Wissmar, R.C., and C.A. Simenstad. 1998. "Variability of Riverine and Estuarine Ecosystem Productivity for Supporting Pacific Salmon." In Change in Pacific Northwest Coastal Ecosystems. G.R. McMurray and R.J. Bailey, editors. NOAA Coastal Ocean Program, Decision Analysis Series No. 11. Pp. 253-301.